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PIPELINE STABILITY IN AN ICE-SCOURED SEABED

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ABSTRACT

Ice scour is a poorly understood phenomenon which occurs when ice (pressure ridge or iceberg) moves while in contact with the seabed. It is of economic significance due to the likelihood of disruption of seabed structures. Current debate centres over the failure mechanisms associated with scour and the consequent subseabed deformations. Phenomenological studies of iceberg scouring by C-CORE have provided the framework for more quantitative analyses wherein the stress and displacement fields below scouring icebergs have been investigated. These studies include excavation of relict ice scours in western Canada where well preserved iceberg scour features from glacial Lake Agassiz have been found. These studies have provided confirmation of subscour deformations associated with scouring, and have indicated a failure mechanism. In addition, observations have been made of ice scour tracks for relatively small "icebergs" (ice pans from the spring breakup) ranging up to approximately 50 tonnes in size, across the St. Lawrence tidal flats near Montmagny, Quebec. The observations have led to the experimental modelling of iceberg processes in the laboratory in order to determine the stress and displacement fields below a scouring iceberg.

KEYWORDS: ice scouring, seabed, icebergs, physical modelling

INTRODUCTION

Ice scouring of the seabed is a ubiquitous feature of most of the coastal regions of northern continents. Figure 1 shows areas in the northern hemisphere where ice scoured features have been documented in the literature and also those areas where extensive ice scour could be expected based on known present and past ice conditions.

Ice scour occurs when ice impacts the seabed. The scour may take the form of a long linear furrow following a relatively straight line or it may be erratic in its path, covering only a few tens of metres or many tens of kilometres. In open waters, such as the east coast of Canada as far south as the southern tip of the Grand Banks, (and sometimes beyond) and in the northern Norwegian Sea, ice scour is normally associated with glacial ice in the form of icebergs. In northern oceans such as the Beaufort Sea and the Barents Sea most of the ice scours are caused by deep keels formed by pressure ridges that impact the seabed. Ice scours are also caused by multi-year ice, ice islands or icebergs in these regions. Figure 2A shows a typical iceberg scour path from a side scan mosaic for the Beaufort Sea caused by deep keels associated with pressure ridges and Figure 2B shows the type of scours that occur off the coast of Labrador, Canada.

The purpose of this paper is to describe the work that has been undertaken to determine the forces and soil displacements that can be expected under a seabed that is being scoured by various ice and seabed interaction processes. This information is important to the development of offshore oil and gas resources as well as other subsea installations such as hydroelectric and communication cables.

DESCRIPTIONS OF THE PROBLEM

When ice impacts the seabed it creates either a furrow or a localized pit (Lewis and Barrie, 1981; Clark and Landva, 1986). On the east coast of Canada, most of the recent scours occur in water depths of 150 to 230m. Scours are found at greater depths but they have been determined to be relict (Fader and King, 1981). Of the scours that have been surveyed on the Grand Banks, most are less than 1.5m deep and it is rare to find a modern scour more than 2m deep. Localized pits occur when an iceberg suddenly impacts the seabed either as a result of rolling and keel deepening, or by the splitting and

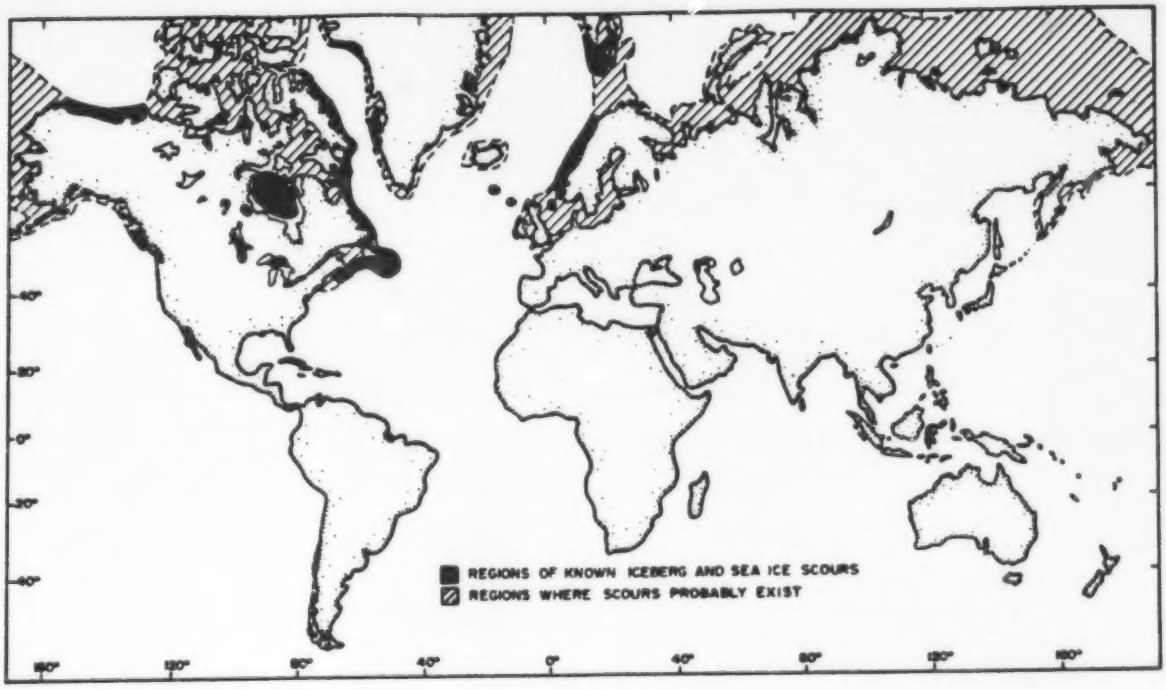


Figure 1 - Areas of probable and known ice scours (after C.M.T. Woodworth-Lynas, C-CORE, 1990)

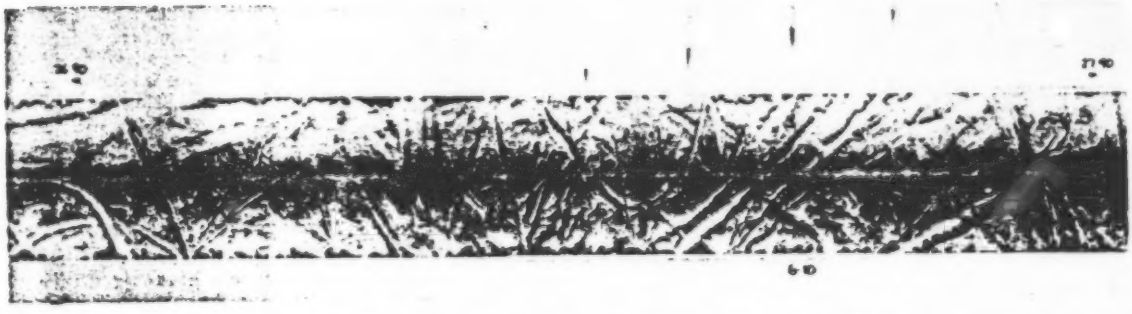


Figure 2A - Side scan mosaic for the Beaufort Sea (Photo courtesy of Shirley McLaren, McGregor Geoscience)

crashing into the seabed as a result of the new configuration. It has been shown mathematically that an iceberg can increase its keel depth by up to 50% simply by rolling as a result of instability caused by gradual ablation (Bass and Peters, 1984). Icebergs splitting and grounding have been observed and it is believed that when this happens under very high sea state a deep localized pit may result (Clark and Landva, 1986). Over 95% of the pits on the Grand Banks that have been surveyed are less than 3m deep but some have been observed to be up to 10m deep. Of those surveyed, only 3.5% exceed 5m in depth (Clark *et al.*, 1986). Theoretical analysis based on the known geotechnical properties of the upper sediments and the ice strength indicates a potential localized pit depth of about 12m (Clark and Landva, 1986).

In the Beaufort Sea scour depths are typically in the range of 0.6m to 2.1m deep (Hnatiuk and Wright, 1983).

The depth of scour can be readily determined by near-surface geophysics and side scan sonar surveys. Analysis of these data will indicate what scour depths might be experienced at a given frequency in order that risk analysis may be carried out to optimize pipeline burial depth. However, the geophysical data does not produce clear evidence of the soil displacement that might be experienced below the scour. This aspect of ice scour has been the subject of intense research at C-CORE for several years.

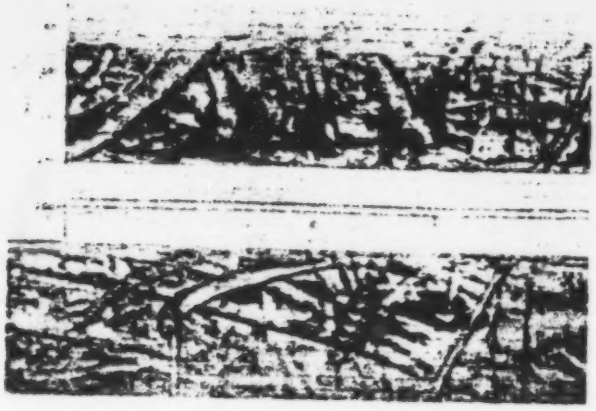


Figure 2B - Side scan mosaic from the coast of Labrador

The first research work on seabed scour began in 1978 when there was a major effort to gather field data. This work included analyses of sidescan sonar as well as manned submersible dives on ice scours to observe specific features and to collect data on shape and soil properties. Over the past five years the thrust of the research work has shifted to more quantitative studies of forces acting on the seabed and the displacement of the soil below the seabed. The importance of this knowledge can be ascertained from the information that in the Beaufort Sea, the development of the first major field, Amauligak, could require up to seven billion dollars. Four billion dollars of this will be required for the field facilities and three billion dollars will be required for the pipeline (Bruce, 1990). The depths of scours and the soil deformation below the scours have a direct impact on the cost of the offshore pipeline. Figure 3 shows the relative cost associated with different ice conditions and hence depth for pipelines (McKeehan, 1990). It is therefore very important to know what loading and displacing will occur on pipelines buried at or below the scour depth in order to determine the potential risks of rupture due to ice impact or soil displacement.

RESEARCH PROGRAM

Research on iceberg scours at C-CORE started in 1978. A comprehensive review of what was known at that time and a number of observations on speculative aspects of the ice scour process were presented in a C-CORE Report (Gustajtis, 1979). At the same time, research on ice scours off the east coast of Canada was being carried out by the Atlantic Geoscience Centre (AGC) as well as a number of oil companies.

The research program on ice scours at C-CORE has since then had the following phases:

1) the collection of phenomenological data
2) analysis of side scan sonar mosaics
3) direct observations of scours from manned submersibles

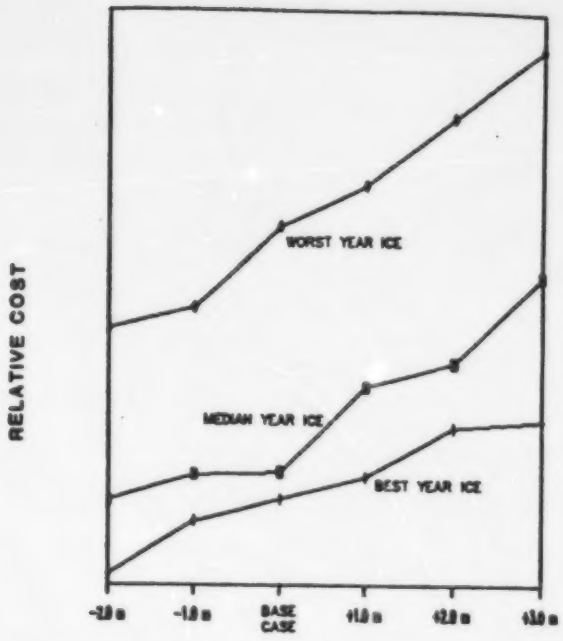


Figure 3 - Relative cost vs. ice conditions and trench depth (after McKeehan, 1990).

4) initiation of studies of relict scours in the Canadian Arctic and Lake
   Agassiz, Manitoba
5) direct observation of small scale scour events with icebergs up to 50 tonnes
   on the flood plains of the St. Lawrence River
6) laboratory modelling of the scour process

Each of these will be briefly described in the following paragraphs:

Collection of Phenomenological Data

This work was initiated in 1978 and continues today. Several reports have been issued (for example, Lewis and Barrie, 1981; Woodworth-Lynas and Guigné, 1989). The studies have defined the morphology of the scours and have provided a significant amount of information on the rates of occurrence. Similar work has been carried out in the Beaufort Sea (Hnatiuk and Wright, 1983). These works have provided a reasonably good basis to determine the average depth of scour, the maximum depth of scour, and the rate of occurrence. The ongoing studies include surveys for repetitive mapping to improve the data base. Nevertheless, there is a good body of data available for both the east coast of Canada and the Beaufort Sea that can be used to determine the potential risk of exceedance of scour beyond a certain depth. In addition, on the east coast of Canada, a study of scours that occurred both upslope and downslope has been carried out

(Woodworth-Lynas *et al.*, 1986a). This has been very informative in that it has shown that scour morphology remains relatively constant over changes in relief of up to 15m. It is clear that an iceberg which maintains a relatively consistent shape and depth of scour while riding up and down slopes of up to 15m change in elevation must produce a significant variation in pressure acting on the seabed.

Analysis of Side Scan Sonar Mosaics

Side scan mosaics have been analyzed to gain better insight into the dating of the scours in addition to the studies of scour morphology. The dating work is carried out by starting with a modern scour of known time and tracing back through scours that it crosses. Analysis has also been made of preferred direction. Figure 4 shows the tracks of iceberg scours taken from a side scan mosaic from the Saglek east study area, Saglek Bank, Labrador. These scours have been analyzed,

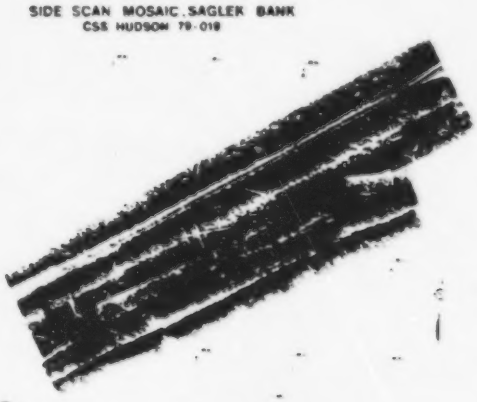


Figure 4 - Side scan mosaic from Saglek Bank

and the resulting rosette is shown in Figure 5 (Woodworth-Lynas *et al.*, 1986a). This shows a preferred orientation in the East-West direction and a secondary preference in the North-South direction. This information can be very useful in selecting pipeline or cable routes (Clark *et al.*, 1987). The analysis of the occurrence of ice scours from the Pullen Block on the Canadian Beaufort Shelf incidates that approximately 6% of the seabed is scoured every year. This indicates that 90% of the seabed would be reworked after 16 years (Lewis and Blasco, 1990).

Direct Observations of Scours from Manned Submersibles

Dives on iceberg scours have been made in cooperation with AGC scientists in the Department of Fisheries and Oceans submersible *PISCES* as well from the *HMCS CORMORANT* using the SDL-1 submersible. These direct observations have been

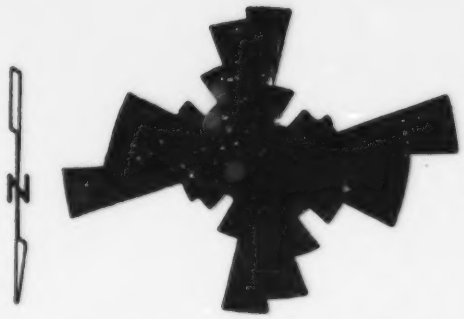


Figure 5 - Scour direction rosette from Figure 4 (After Woodworth-Lynas *et al.*, 1986a)

very useful in developing a fuller understanding of scour morphology and failure mechanisms. In addition, the dives have confirmed that there is considerable attrition of the ice as it scours the seabed. Figure 6 shows the relatively fresh scour with large pieces of ice still embedded below the scour surface. Reconnaissance of the scours indicate a large number of melt out depressions where ice had been embedded during the scour process. It is thus very clear that the ice fails as the soil fails so as to produce the most efficient shape providing the least resistance to the advancing ice. Although icebergs have an infinite variety of shapes and keels the long linear scours have a relatively consistent shape. That shape is approximately a U-form but many other types of scours can also be found on the seabed. Other forms of scours include the so-called crater chain where an iceberg bounces along the seabed touching down frequently but not creating the same type of gouge as for a scour in intimate contact with the seabed. A third type is the chatter-mark scour where an iceberg wobbles along its specific path almost neutrally buoyant, not enough to bounce but also with non-sufficient contact pressure to produce a continuous, uniform scour. The reproduction of the sidescan mosaic of Figure 2B shows examples of all of these scour types.

Figure 6 - Relatively fresh scour with large pieces of ice still embedded below the scour surface.

Initiation of Studies of Relict Scours in the Canadian Arctic and Lake Agassiz, Manitoba

Relict scours were first studied on King William Island. At that time cross trenches were cut through an iceberg scour and a terminal scour to examine the subscour and infill features (Woodworth-Lynas *et al.*, 1986b). The soil at this site consisted of a very heterogeneous till-like material with very little clay binder. The most interesting feature revealed in the excavation was the infill of relatively fine sand. At that time a model was suggested that involved the winnowing of sand that subsequently settled back in the scour after the iceberg had passed. This may well be the case but other mechanisms may also account for the sorting. The presence of permafrost did not allow excavation to the bottom of the zone affected by the scour.

The most comprehensive relict scour study undertaken has been the study initiated in 1986 and continuing today at the Lake Agassiz scour field near Lorette, Manitoba. Figure 7 shows an aerial photo of the scour tracks that can be seen. These scours were created by icebergs from the continental ice sheet which bordered glacial Lake Agassiz about 9000BP. The water depth at that time has been inferred to be about 100m. The sub-soil at the site consists of a highly plastic clay which at the time of the scouring events had previously been subaerially exposed for over 300 years (Woodworth-Lynas and Guigné, 1990). As a result, the clay was over consolidated and was able to develop well-defined shear planes. With this particular clay a highly polished fabric is developed after a minor amount of shear dislocation along a shear plane. The fieldwork has revealed very definite and well-defined shear planes that suggest a Prandtl-type failure wedge (Terzaghi, 1943) directly underneath some of the iceberg scours. These features strongly suggest a bearing capacity failure in the soil mass below some of the scours.

Direct Observation of Small Scale Scour Events with Icebergs up to 50 tonnes on the Flood Plains on the St. Lawrence River

Two field programs have been carried out in the St. Lawrence Estuary to observe small scale iceberg scours. An example of scour tracks is shown in Figure 8. Excavations have been made through some of the scour tracks, and sub-scour soil failure features similar to those revealed in the relict scours have been indicated. The soil on the flood plain is much weaker than that of the relict scours but the depth of disturbance has been determined by making small scale vane shear tests. The disturbed soil is much weaker than the undisturbed soil surrounding it. These observations tend to confirm the sub-scour failure mechanism observed for the relict scours in glacial Lake Agassiz.

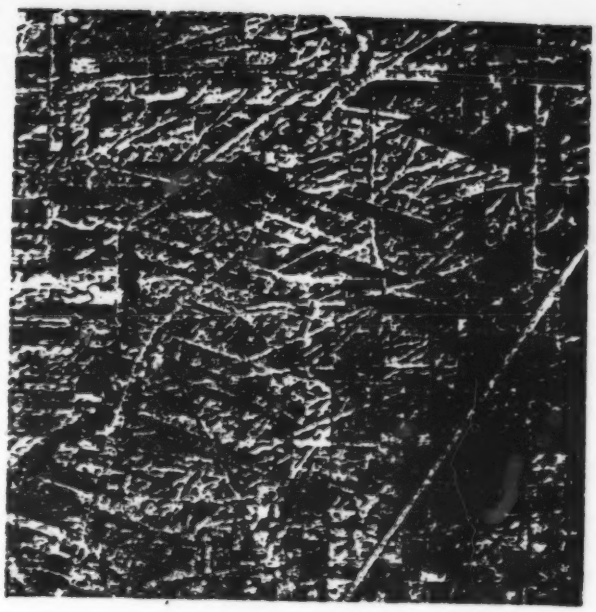


Figure 7 - An aerial photograph of the Lorette Region in Manitoba. The road in the photograph is the Trans-Canada Highway. North is to the right.

Figure 8 - A typical scour in the St. Lawrence (After Poorooshasb and Clark, 1990).

Laboratory Modelling

Laboratory modelling has been carried out at Memorial University in a specially designed scour tank. The overall tank consists of two compartments, both of which can be flooded with water and one of which can also include wave action.

Previous modelling work relevant to ice scour has been carried out by several researchers and the results have been reported in the literature (Harrison 1972; Chari, 1979, 1980) In addition, proprietary work has been sponsored by various oil companies (Fenco Ltd. 1975; Golder Associates Ltd. 1989). Other proprietary studies have been carried out by industry and the results have been made available to the authors.

Previous laboratory modelling led to the concept of the iceberg as a rigid indentor and of a ploughing action with very little vertical force acting on the seabed. The phenomenological data, and in particular that recorded from the studies of relict scours and the direct observations of small scale scours, have suggested that the vertical force may be sufficient to cause failure and displacement of the soil below the scour. These observations were used in designing the scour tests conducted in the iceberg scour tanks at Memorial University.

The first set of tests was carried out in a clayey silt material. Although these tests were pilot studies to assess the model iceberg and investigate the appropriate scour depth for testing, a considerable amount of useful information was obtained (Poorooshasb *et al.*, 1989).

The most comprehensive model test program was carried out in a sand bed which was prepared at two different densities. This work was sponsored by the Canada Oil and Gas Lands Administration and has been reported extensively elsewhere and recently presented at an ice scour workshop (Poorooshasb, 1989; Poorooshasb and Clark, 1990). The soil was instrumented so that the sub-scour displacement could be determined after the scouring event. Instrumentation consisted of small steel ball bearings whose course could be tracked as well as flexible lines of solder placed across the scour track at various depths below the maximum scour depth. In addition, the iceberg was instrumented with pressure cells so that the stress on the soil at the bottom of the scour as well as the stresses on the attack face could be measured. A fixed scour cut depth was set and the stress variation was measured through the course of the test. In each test, the model scoured through a loose sand and a denser sand. The different densities for the two sections were obtained by varying the height and horizontal speed at which the sand was rained down from a hopper to the test bed. A total of 4 tests were carried out and these are further discussed below.

TECHNICAL DATA AND RESULTS

Silt Tests

Two tests were carried out in gravity consolidated silt at Memorial University's scour tank facility. The prepared silt bed measured 5m in length by 3m in width and was 0.37m deep. The measured (hand vane) shear strength of this silt varied from 4 to 10kPa. This was overlain with a 10-20mm layer of silty clay with shear strength of about 10kPa and a plasticity index of about 8 (Poorooshasb and Clark, 1990). Six pore pressure transducers were buried in the silt test bed at various depths and horizontal distances off centreline.

The model iceberg was constructed as shown in Figure 9. Aluminum plates were welded together to form the shape and the model was mounted as in Figure 10. This mounting system allowed the model to pitch and heave while controlling horizontal movement

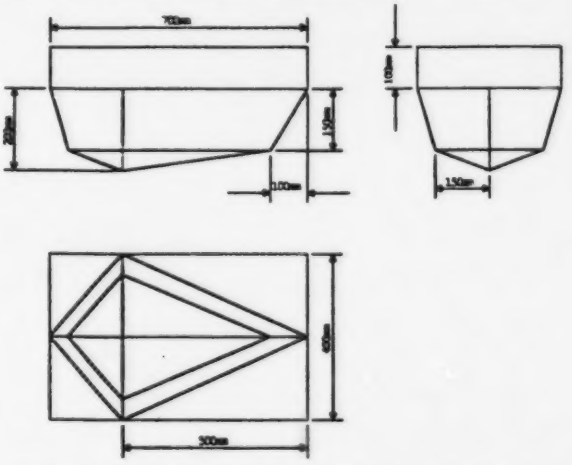


Figure 9 - Model Iceberg Used in the Silt Tank (After Poorooshasb and Clark, 1990).

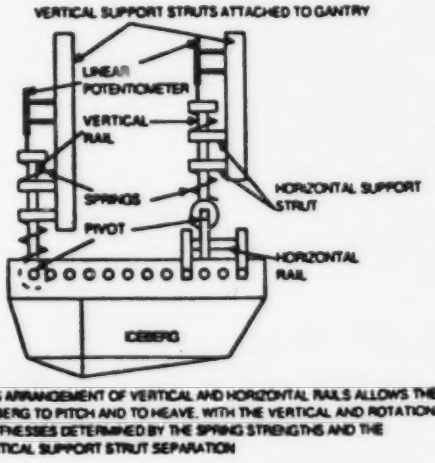

VERTICAL SUPPORT STRUTS ATTACHED TO GANTRY
LINEAR POTENTIOMETER
VERTICAL RAIL
SPRINGS
PIVOT
HORIZONTAL SUPPORT STRUT
HORIZONTAL RAIL
ICEBERG
THIS ARRANGEMENT OF VERTICAL AND HORIZONTAL RAILS ALLOWS THE ICEBERG TO PITCH AND TO HEAVE. WITH THE VERTICAL AND ROTATIONAL STIFFNESSES DETERMINED BY THE SPRING STRENGTHS AND THE VERTICAL SUPPORT STRUT SEPARATION

Figure 10 - The mounting system for the model iceberg (After Poorooshasb *et al.*, 1989).

(Poorooshasb *et al.*, 1989). The mounting system was in turn connected to a gantry which spanned the test bed and was used to drive the iceberg. The speed of the gantry was kept constant at 0.06ms^{-1} for these two tests.

The results of the tests conducted in the silt tank are fully discussed by Poorooshasb *et al.* (1989). Two scour depths were chosen for the tests: the first at an average scour depth of 40mm and the second at an average scour depth of 70mm. The purpose of these experiments was to measure and observe the following (Poorooshasb *et al.*, 1989):

1. surface morphology and how it changed after scouring.
2. subsurface deformations shown by displacement of horizontal layers created by sediment deposition of fine sand.
3. pore pressure response during scouring.

Test 1 did not penetrate the clay surface but rather created a groove which caused a deformation of sublayers to a depth of 0.2m (5 scour depths). This was observed by excavating the scour after completing the tests. Pore pressure response up to 6kPa at considerable distances from the scour were recorded (Poorooshasb and Clark, 1990). Typical data from these tests are shown in Figures 11-13.

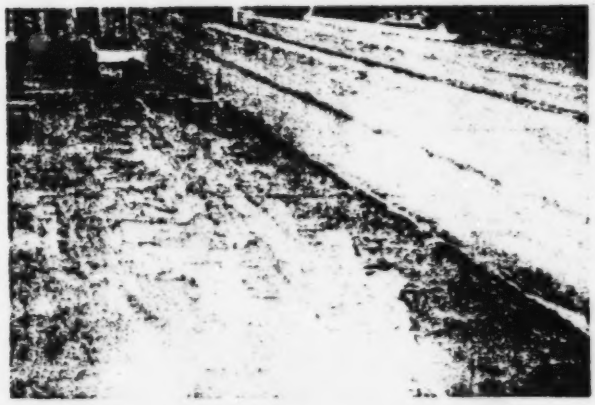


Figure 11 - Surface morphology of shallow and deep scours in silt (After Poorooshasb and Clark, 1990).

For test 2 the model iceberg was set at a depth sufficient to penetrate the silty clay crust. An action, not unlike that of a bulldozer, pushed large pieces of this crust upwards and outwards. Again deformations below the scour depth was noted but in the area of the scour centreline the deformation of the sand laminations were not traceable (Poorooshasb and Clark, 1990).

Sand Tests

The tank adjacent to the silt tank was used for sand scour modelling and four scour model tests were conducted. The procedure and results of these tests are presented in much greater detail by Poorooshasb (1989) but will be summarized here.

The following were the purposes of these experiments:
1. to investigate the extent and magnitude of the displacement field below the scours.
2. to determine if attack angle[1] and model width affect the scour process
3. to measure the forces required to create the scours.

The model sand bed was 3m in width, 8m in length and 0.6m deep. The sand was a clean dry silica sand with a grain size distribution as shown in Figure 14. The test bed was prepared as shown in Figure 15. The depositional procedure allowed the sand to be laid between the limits of approximately 0% (loose) and 60% (dense) relative density. The instrumentation was placed in the sand as the test bed was constructed.

The iceberg model is shown in Figure 16. Four different configurations of the model were possible by varying the attack angle and width. The model iceberg was bolted to a rigid gantry - mounted frame. This frame was set up to provide a scour depth of 75mm. Pressure and load cells were located at various positions on the model iceberg face and frame to measure face pressures and horizontal and vertical forces. The iceberg scour was conducted at a velocity of 0.06ms^{-1}.

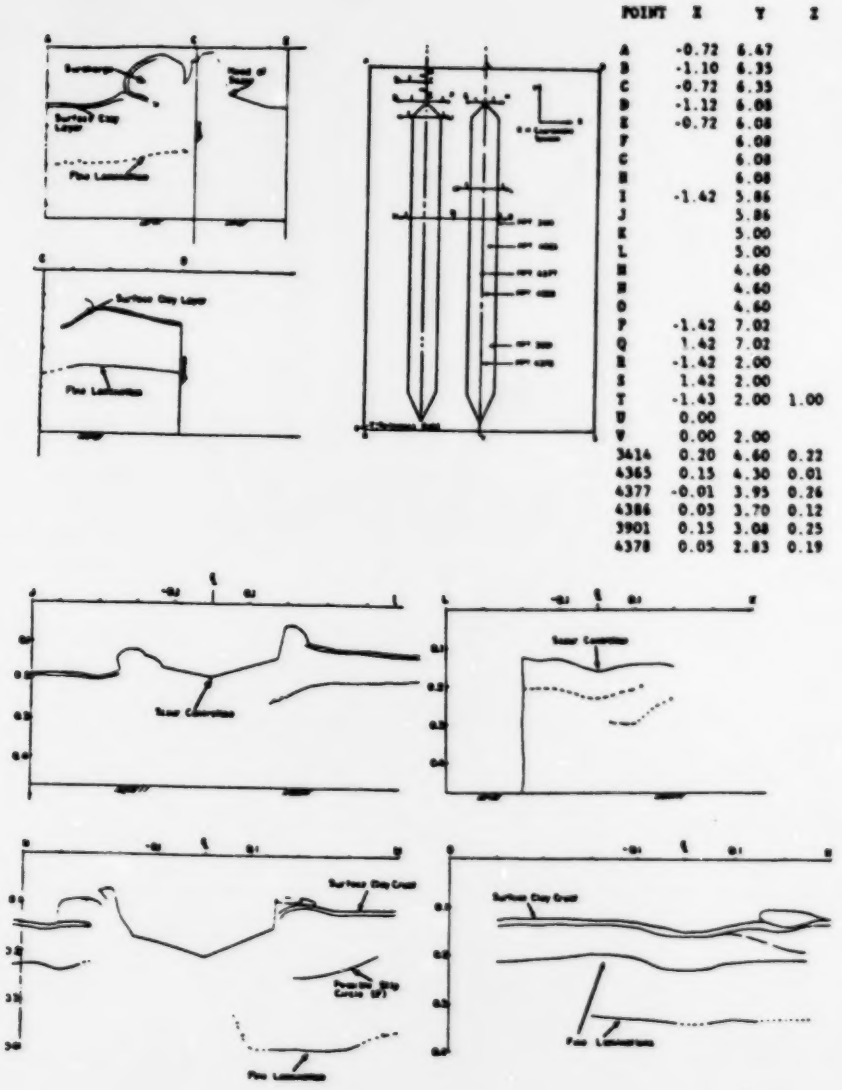
Load cells and various displacement markers were placed in the bed between sand rainings. The displacement markers consisted of 0.5" steel ball bearings, and lengths of solder laid across the scour path at various depths. The ball bearings (each with an identification number) were placed at predetermined positions as preparation of the bed took place. The positions of the ball bearings (before and after scouring) were determined through the use of a pointer system mounted on the overhead gantry. The solder strands were laid and their position recorded with the same instrument. By carefully excavating after the scouring event, new positions of the displacement markers could be recorded and this data used to determine total displacement vectors.

The variable parameters for the four tests are shown in Table I (Poorooshasb and Clark, 1990).

TABLE I

	TEST 1	TEST 2	TEST 3	TEST 4
Attack Angle (Degrees)	15	15	30	15
Width (mm)	430	860	860	860
Scour Depth (mm)	75	75	75	75
Relative Density Loose sand (%)	8	8	-2	8
Relative Density Dense sand (%)	36	29	46	60

[1]Angle between horizontal and the surface of the model iceberg which first contacts the sand and as shown in Figure 16 (Poorooshasb, 1989).



POINT	X	Y	Z
A	-0.72	6.47	
B	-1.10	6.35	
C	-0.72	6.35	
D	-1.12	6.08	
E	-0.72	6.08	
F		6.08	
G		6.08	
H		6.08	
I	-1.42	5.86	
J		5.86	
K		5.00	
L		5.00	
M		4.60	
N		4.60	
O		4.60	
P	-1.42	7.02	
Q	1.42	7.02	
R	-1.42	2.00	
S	1.42	2.00	
T	-1.43	2.00	1.00
U	0.00		
V	0.00	2.00	
3414	0.20	4.60	0.22
4365	0.15	4.30	0.01
4377	-0.01	3.95	0.26
4386	0.03	3.70	0.12
3901	0.15	3.08	0.25
4378	0.05	2.83	0.19

Figure 12 - Subsurface deformations underneath scour in silt tank (After Poorooshasb and Clark, 1990).

Typical examples of data and results obtained from the tests are shown in Figures 17-27.

Data obtained during these tests show that soil density significantly affects the amount of subscour deformation. Figures 21 and 22 show the displacements of the solder strands after test 4. In the loose soil, deformations of the solder strands were observed to a depth 65mm below the scour while in the dense soil deformations were restricted to immediately below the scour (5mm) (Poorooshasb *et al.*, 1989).

Attack angle was also observed to affect subscour deformation. Test 3 was set at a 30 attack angle and very little subscour disturbance was detected in either the loose or dense sand (Poorooshasb *et al.*, 1989)

The effect of the variation of the relative density and attack angle on the forces acting on the face of the iceberg was also recorded. Table 2 summarizes the forces. Test 1 was corrected to account for the fact the model width was only half that in the other three tests. $F_{v\,pk}$ and $F_{h\,pk}$ represent the peak vertical and horizontal forces measured in the test, θ represents the angle of resultant forces and $F_{v\,loose}$ and $F_{h\,loose}$ represent the average vertical and horizontal stresses in the looser soil (Poorooshasb and Clark, 1990). Two points can immediately be observed by looking at the data. The first is that the magnitude of the forces

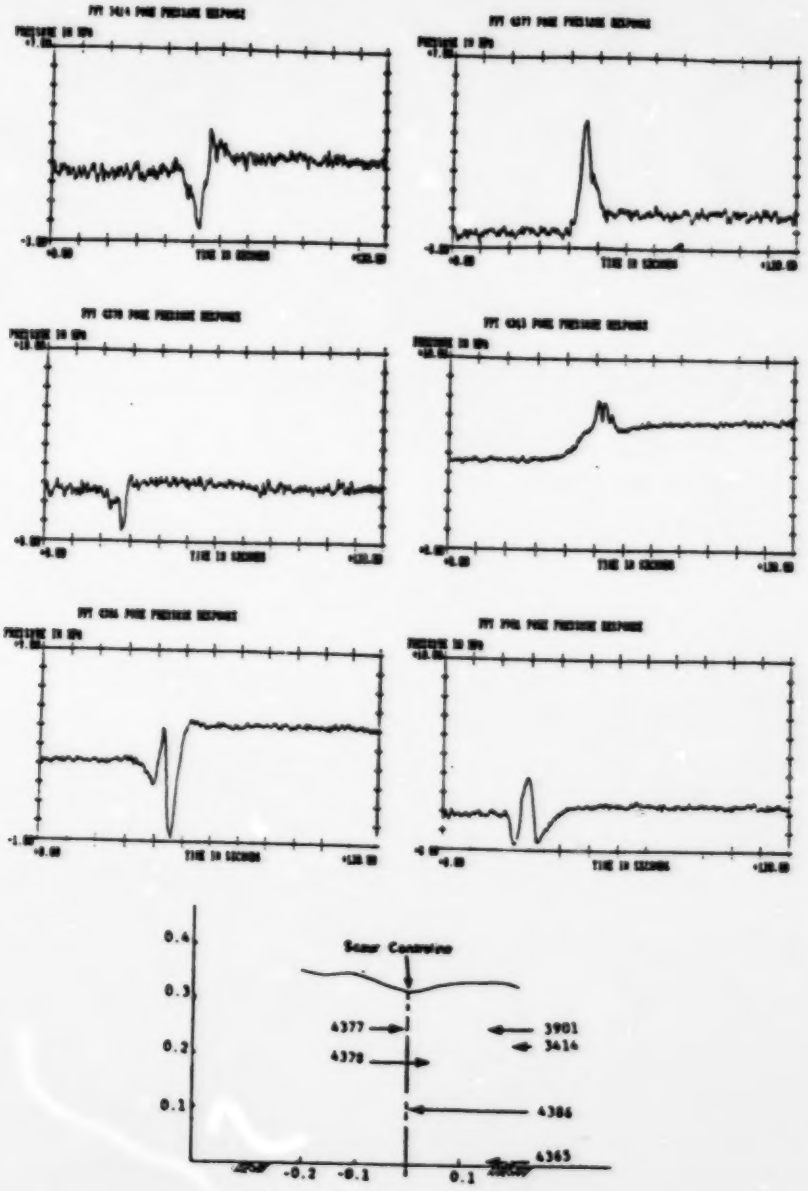


Figure 13 - Pore pressure changes in vicinity of scour in silt tank (After Poorooshasb and Clark, 1990).

TABLE 2

Test	$F_{v\ pk}$	$F_{h\ pk}$	θ_{dense}	$F_{v\ loose}$	$F_{h\ loose}$	θ_{loose}
1	6.5	5	50	2.5	2	50
$1_{(corr)}$	13	10	50	5	4	50
2	9	8	49	7.25	6.5	48
3	7.5	8.5	41	2.25	2.75	40
4	12.5	9.5	51	8.5	7.5	49

from test 3 (attack angle 30) is less than that of the other tests and only in this test are the horizontal forces greater than the vertical. The second point is that the angle of the resultant force was greater by 8-10 for the other three tests (Poorooshasb and Clark, 1990).

Figure 28 shows the pressure cell locations on the iceberg as well as its coordinate system. The stresses measured on the iceberg are summarized in Table 3 and σ_n refers to maximum stress recorded at point n. The most obvious observation here is that

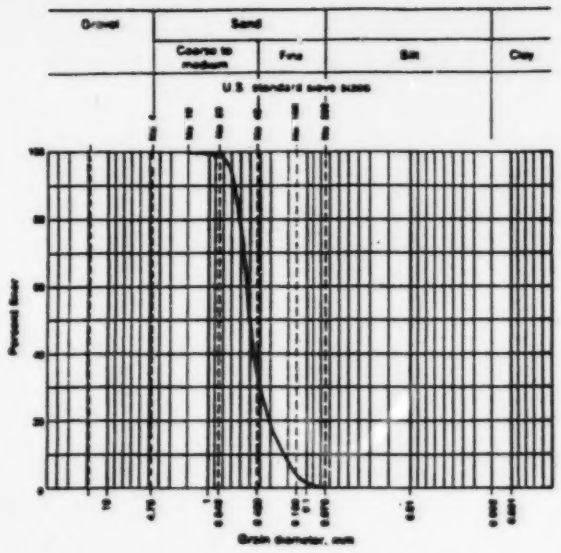


Figure 14 - Grain size analysis of sand used in model tests (After Poorooshasb and Clark, 1990)

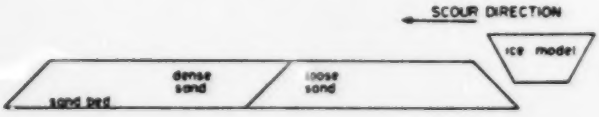


Figure 15 - Set up of the sand bed

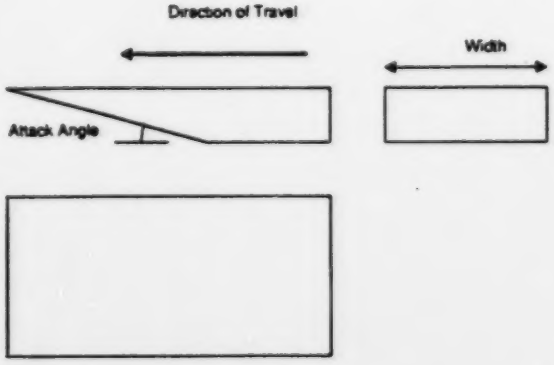


Figure 16 - The model iceberg used in the sand tests (After Poorooshasb and Clark, 1990).

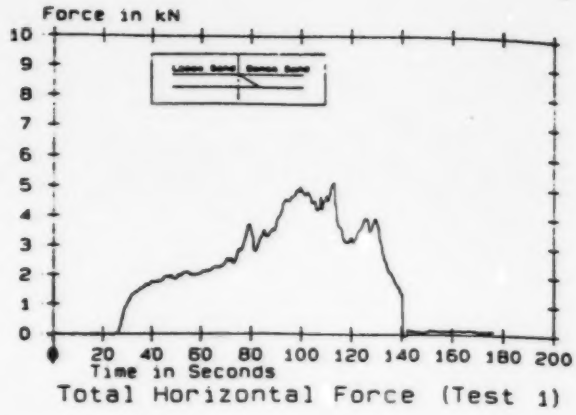


Figure 17 - (After Poorooshasb and Clark, 1990)

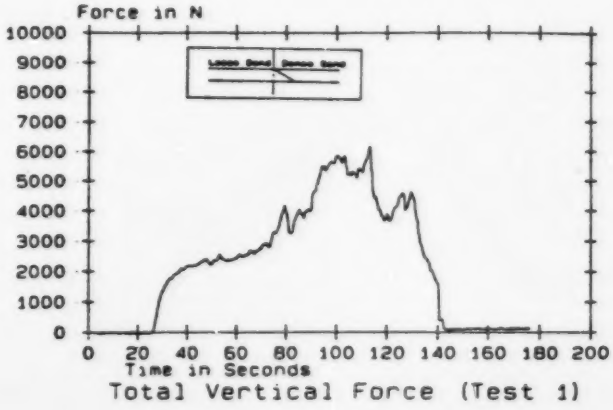


Figure 18 (After Poorooshasb and Clark, 1990)

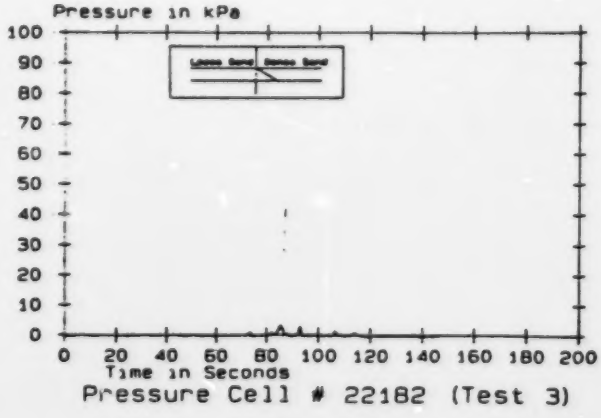


Figure 19 - Pressure cell located behind the inflexion line (After Poorooshasb and Clark, 1990)

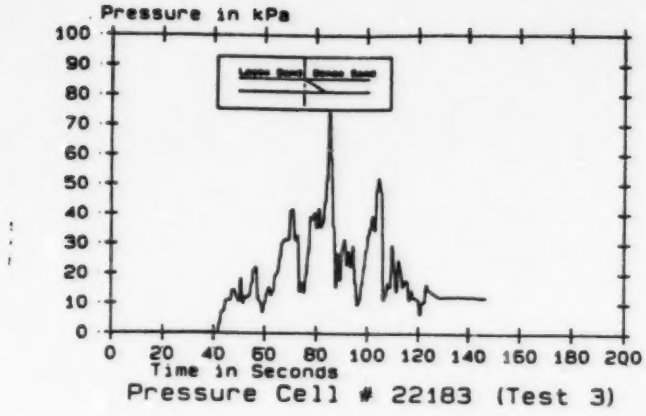


Figure 20 - Pressure cell located just forward of the inflexion line (After Poorooshasb and Clark, 1990).

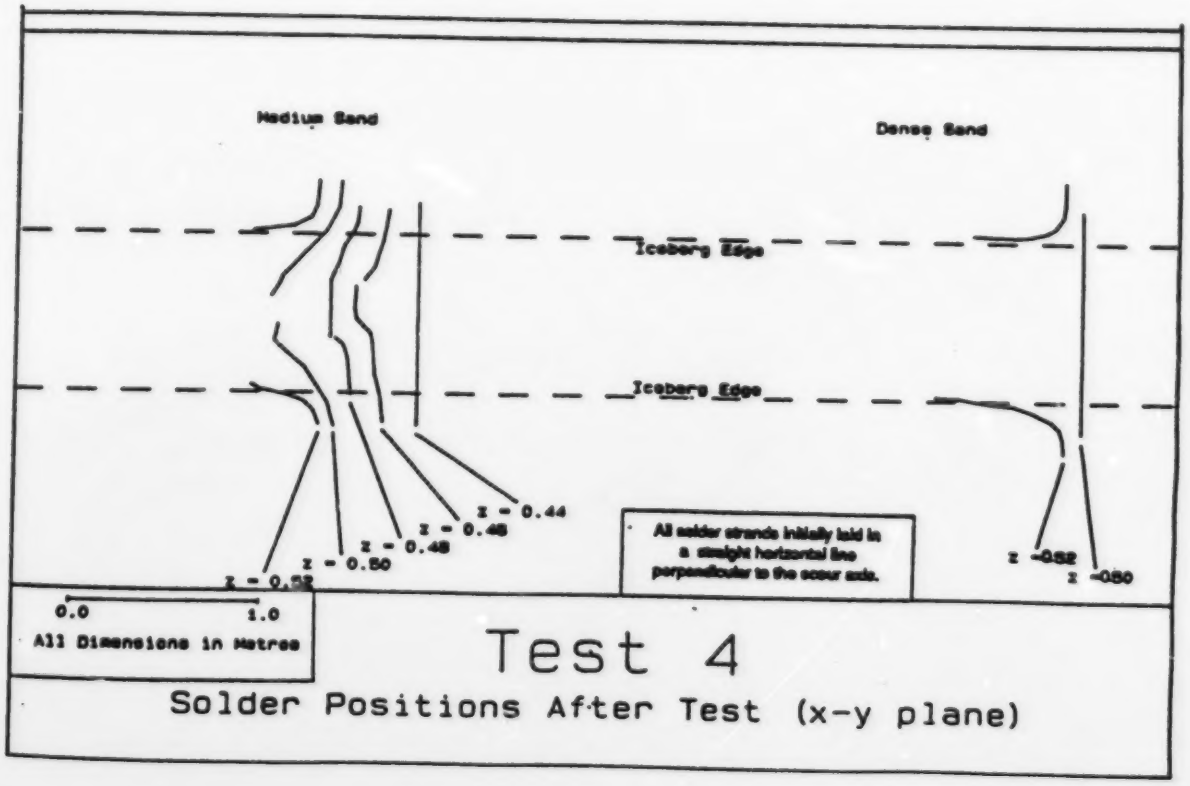


Figure 21 - Solder displacement, plan view (After Poorooshasb and Clark, 1990).

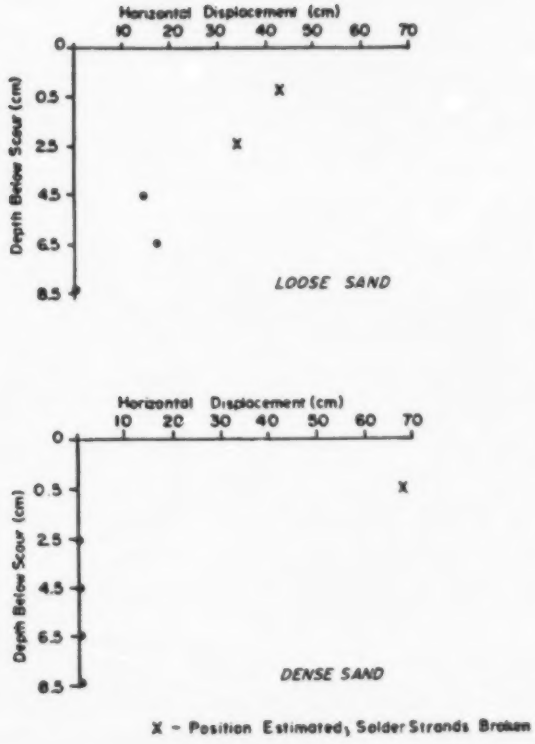


Figure 22 - The variation of axial displacement with depth below scour cut level. For loose and dense sands.

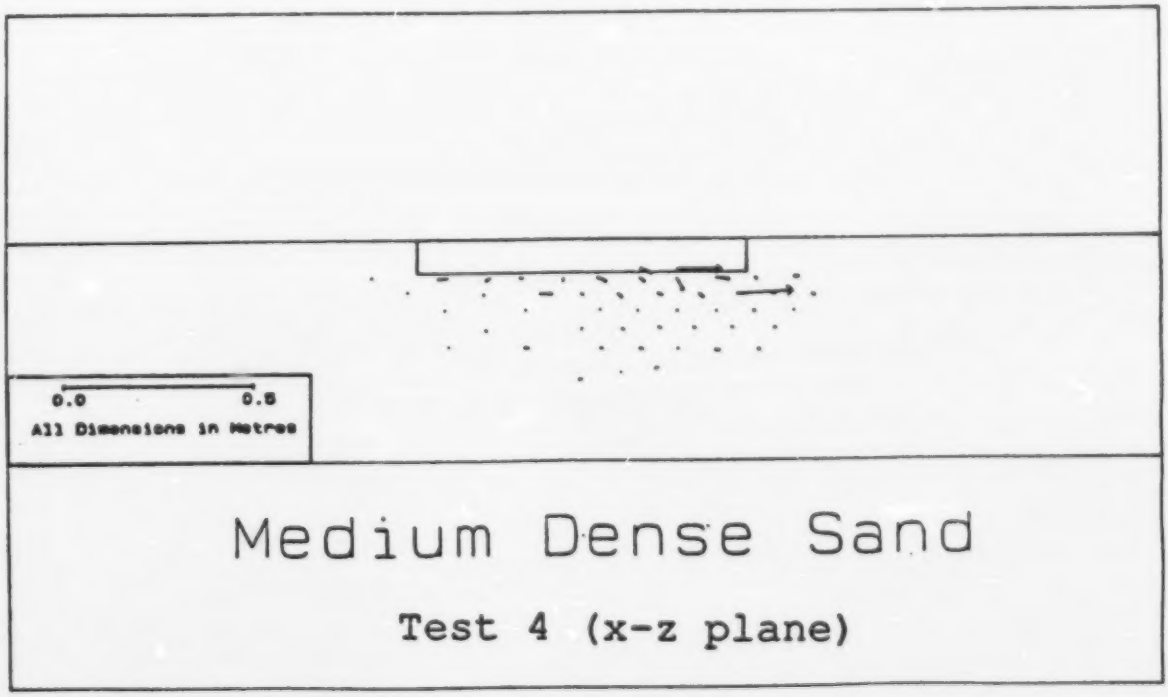


Figure 23 - Ball displacements, cross sectional view, scour created perpendicular to page (After Poorooshasb and Clark, 1990).

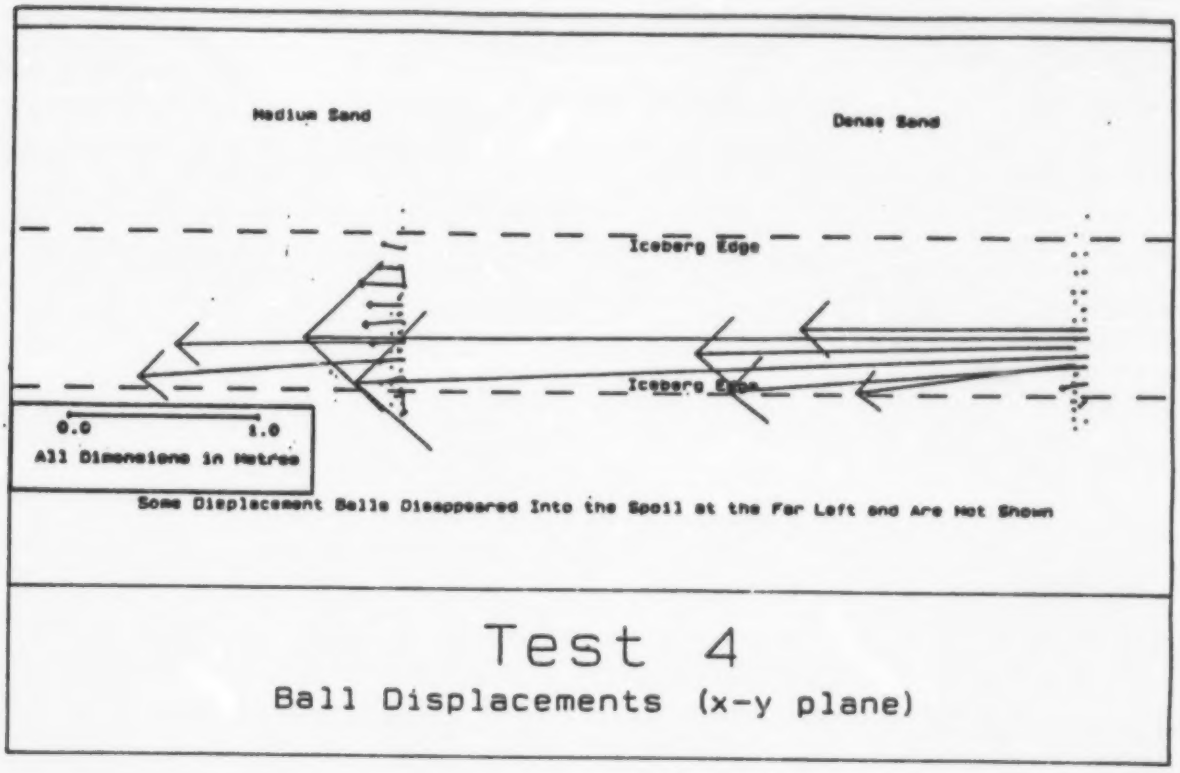


Figure 24 - Ball displacements, plan view scour created from right to left (After Poorooshasb and Clark, 1990).

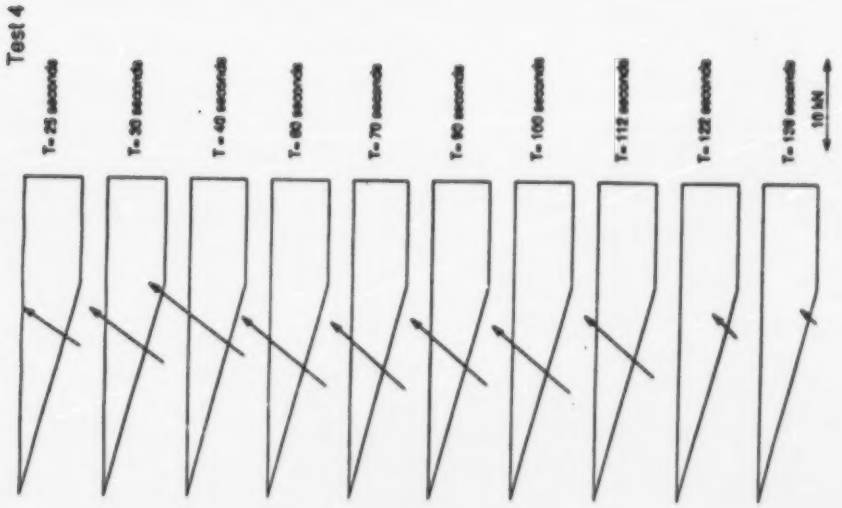


Figure 25 - Total force vectors (After Poorooshasb and Clark, 1990).

Figure 26 - Creation of scour in Test 1 (After Poorooshasb and Clark, 1990).

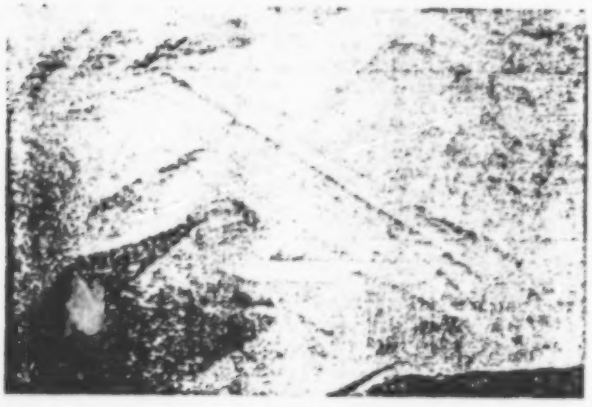
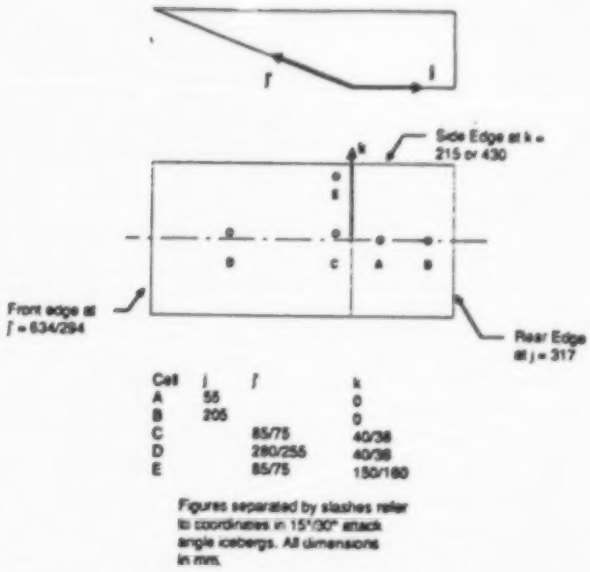


Figure 27 - Excavation of scour in Test 2 showing solder strands (After Poorooshasb and Clark, 1990).



Cell	i	f	k
A	55		0
B	205		0
C		85/75	40/38
D		280/255	40/38
E		85/75	150/160

Figures separated by slashes refer to coordinates in 15°/30° attack angle icebergs. All dimensions in mm.

Figure 28 - Coordinate system on iceberg and pressure cell locations (After Poorooshasb and Clark, 1990).

the stress levels from the cells located at Points A and B (which are located behind the inflexion line, on the horizontal base) are very small as compared to those values recorded at C, D and E. Therefore it would appear that almost all the force which is applied to the model iceberg arises from the frontal attack plate (Poorooshasb and Clark, 1990).

Total stress cells were also placed in the soil bed at predetermined locations. Figure 29 shows a typical plot of the total stress variation as the iceberg scoured over the cell. The total stress dips as the iceberg approaches, then rises sharply and then falls off again to a steady state. This steady state value after the scour pass corresponds well with the expected drop in total stress due to the removal of 75mm of sand. A summary of the total stress measurements recorded during test 3 and 4 are shown in Table 4, where the depth refers to the depth below the bottom of the scour and the offset refers to the distance from the centreline of the scour. A detailed discussion on these results can be found in Poorooshasb *et al.* (1989).

TABLE 3

Test	σ_a(kPa)	σ_b(kPa)	σ_c(kPa)	σ_d(kPa)	σ_e(kPa)
1	10	10	120	50	90
2	5	10	50	20	50
3	5	0	75	35	75
4	3	3	45	38	59

TABLE 4

Test ID	cell	Density Dip (kPa)	Stress Rise (kPa)	Stress Change (kPa)	Stress (mm)	Depth (mm)	Offset
3	O	1350	0	5	-1.8	70	4
4	A	1420	0	9	-1	40	-3
4	C	1420	0	9	1	60	-442
3	A	1500	-1.5	9	-1.8	125	-6
3	C	1500	-3	5	-1.5	75	-5
4	O	1350	-5	14	-8	120	-10
4	D	1350	-1	15	-1.5	75	-57

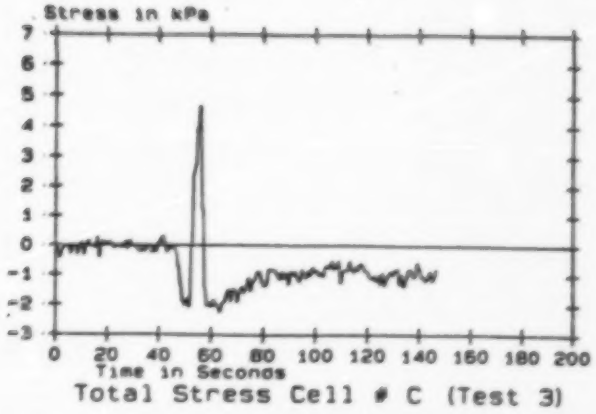


Figure 29 - Total stress on horizontal plane 75mm below scour centreline (After Poorooshasb and Clark, 1990)

DISCUSSION

Conventional seabed survey techniques such as side scan sonograms and direct observations from ROV's and manned submersibles are capable of providing statistics on depth and frequency of scour that will allow risk assessment of a seabed installation experiencing a direct impact with a scouring iceberg. Under certain conditions of seabed soils and iceberg size (obviously related to water depth) the seabed perturbation will be limited to the depth of the scour or to a very shallow zone below the scour as suggested by Palmer (1990). In cases where the vertical load associated with a scouring iceberg exceeds the bearing capacity of the soil, the soil will fail and subsoil perturbation will be much more extensive.

The subscour excavations at Lorette, Manitoba showed convincing evidence of bearing capacity failure below the scours. Similar evidence was found in the excavations below small scours on the St. Lawrence River tidal flats. The lab model tests in the soft saturated clayey silt showed strong evidence of subscour deformation according to the pore pressure response shown in Figure 13 and as seen from excavations through the scour. The sand bed tests showed subscour deformations consistent with bearing capacity failure for the loose sand but bearing capacity failure did not occur in the denser sand, even though the stress acting on the bottom of the iceberg was greater. Indeed, the tests in the denser sand showed results similar to the physical model tests reported by Been (1990) and in keeping with the mathematical model proposed by Palmer (1990). The most important factors controlling the subscour deformation as indicated by the sand bed model tests are density of the soil and angle of attack of the iceberg.

It was postulated in a previous publication (Clark and Landva, 1986) that an iceberg could scour by either a bulldozing action when the front face of the keel is pushed into the seabed or by a trailing keel as the iceberg adjusts to the scour attack position of least resistance. Direct observations of fresh scours which reveal ice melt out depressions and ice blocks that have spalled from the keel (ice failure) suggest that the angle of attack adjusts to that of least resistance as it scours and in the process tends to the trailing keel scour mode. Side scan mosaics also indicate that icebergs will rotate during scour, as shown by Figure 30, and are very likely to continue to scour in a trailing keel mode. This has important implications not only to the depth of scour but also to the vertical pressure acting on the seabed and the potential for subscour bearing capacity failure. For a given cut depth, the seabed will impart a greater vertical force on a trailing keel with a small attack angle than on a bulldozing keel with a sharp attack angle. The most likely scenario, therefore, is that a bulldozing keel, in an unstable configuration, will rotate to a trailing keel configuration and thereby reduce in draft.

Figure 30 - Side scan record showing pit created from rotating iceberg.

Irrespective of the keel configuration as it contacts the seabed, the greatest deformation will occur in the scour zone directly in front of the berg as shown in Figure 31, an area in which total reworking of the soil takes place. Subscour deformation may be restricted to that caused by bearing capacity failure or passive earth pressure failure. A bearing capacity failure beneath the scour will result in a wedge of soil being pushed down but there will be very little lateral deformation in the zone of radial shear or in the passive wedge beyond the zone of radial shear as shown by Figure 31. The design of subsea pipelines will be primarily governed by deformation in the subscour region. Present technology can be used to provide a reasonable estimate of the forces and soil displacement that would need to be considered for a subsea installation, such as a pipeline, in the scour vicinity. The test results suggest that a "safe" burial depth would be approximately one scour

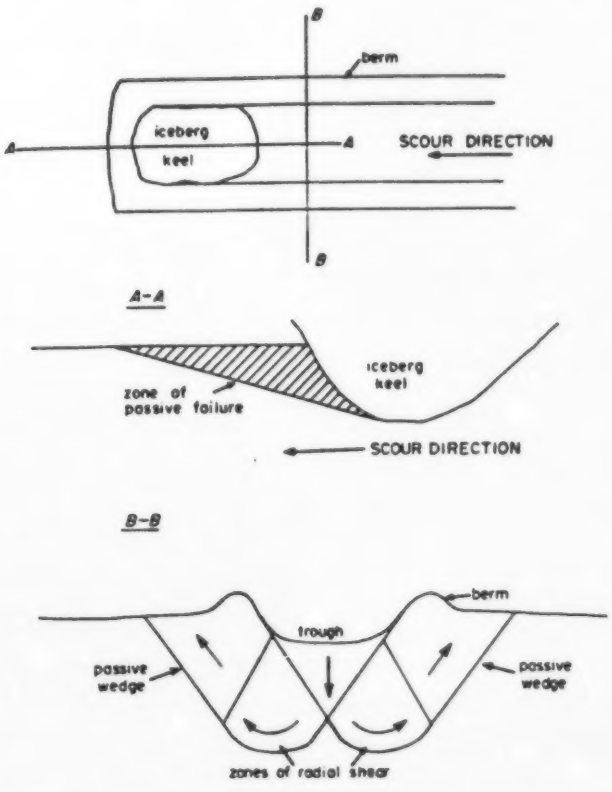


Figure 31 - Soil failure mechanisms due to iceberg scour.

depth below the maximum depth of scour or twice the depth of the maximum scour as measured from the seabed. The soil deformation from a bearing capacity failure may extend below that depth but the absolute deformation would likely be very small and likely within tolerable limits for the pipeline.

The subscour deformation under the keel pressure ridge as experienced in the Beaufort Sea is not so clear. The vertical load acting on the scouring keel will depend upon the ride up of the keel and on the mass of ice it carries with it. It is very likely that the driving forces transmitted through the surrounding ice sheet are much higher than driving forces that can be experienced on a free floating iceberg. An iceberg driven by pack ice would experience similar driving forces to those acting on a pressure ridge keel in the Beaufort Sea. Extensive information is available on the depth of scours in the Beaufort Sea and on the frequency from repetitive mapping surveys but very little information is available on the motions of the pressure ridge as scour occurs.

The available data on iceberg scour and the predictive models would enable the establishment of a safe burial depth for pipelines in both the Beaufort Sea region and the east coast of Canada. However, it is very likely that the design would have to be very conservative. Future studies are required to obtain a better definition of subscour soil deformation particularly under the keels of pressure ridges in order that more cost-effective design can be achieved for offshore pipelines in ice scoured seabeds.

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